Brittle-ductile coupling : Role of ductile viscosity on brittle fracturing

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[1] Localized or distributed deformations in continental lithosphere are supposed to be triggered by rheological contrasts, and particularly by brittle-ductile coupling. A plane-strain 2D finite-element model is used to investigate the mechanical role of a ductile layer in defining the transition from localized to distributed fracturing in a brittle layer. The coupling is performed through the shortening of a Von Mises elasto-visco-plastic layer rimed by two ductile layers. By increasing the viscosity of the ductile layers by only one order of magnitude, the fracturing mode in the brittle layer evolves from localized (few faults) to distributed (numerous faults), defining a viscosity-dependent fracturing mode. This brittle-ductile coupling can be explained by the viscous resistance of the ductile layer to fault motion, which limits the maximum displacement rate along any fault connected to the ductile interface. An increase of the viscosity will thus make necessary new faults nucleation to accommodate the boundary shortening rate. **Citation:** Schueller, S., F. Gueydan, and P. Davy (2005), Brittle-ductile coupling: Role of ductile viscosity on brittle fracturing, *Geophys. Res. Lett.*, *32*, L10308, doi:10.1029/2004GL022272.

1. Introduction

[2] Continental lithospheric deformation can be either localized or distributed. For instance, extension of continents can result either in narrow rifts (Rhine graben) or in wide rifts (Basin and Range Province) [*Buck*, 1991]. In many cases, these contrasting deformation modes are supposed to result from the competition between two mechanisms: brittle failure and viscous flow. These two mechanisms are vertically coupled in the continental lithosphere [*Ranalli*, 1995]. Localization can also take place in the ductile regime (mylonitic fabrics). Such ductile strain localization is however not studied here, and focus is made on the brittle-ductile coupling.

[3] Analogue experiments at the scale of the lithosphere have demonstrated the role of viscous layers on the level of fracturing within brittle layers in compressional settings [*Davy and Cobbold*, 1991; *Sornette et al.*, 1993] or in extensional settings [*Brun*, 1999, and references therein]. *Davy et al.* [1995] and *Bonnet* [1997] show that the ratio of the ductile strength over the brittle strength could explain the transition from a localized damage mode (low ductile/brittle strength ratio) towards homogeneous shortening (high ductile/brittle strength ratio). The ductile strength therefore apparently defines a change in the brittle deformation mode. Several numerical analyses also present evidences for brittle-ductile coupling within the lithosphere. The amount of strain softening and the thicknesses of the high strength layers of the lithosphere are shown to control the development of highly localized zones [*Lavier et al.*, 2000; *Frederiksen and Braun*, 2001; *Behn et al.*, 2002]. Moreover, *Montési and Zuber* [2003] show that fault spacing, in a brittle layer overlying a semi-infinite viscous fluid, increases with increasing ductile viscosity. To explain these features, *Huismans et al.* [2005] propose to balance the energy dissipated in the brittle crust and in the ductile crust. This approach could explain the observed transition from a localized deformation for low viscosity towards an almost homogeneous pure shear deformation for higher viscosity. However, none of these studies pointed out the limitation imposed by the viscous layer on the fault displacement.

[4] The aim of this study is thus to constrain by numerical means the mechanical role of the ductile layer in defining the transition from localized to distributed fracturing in the brittle layer in a compressional setting. We will show that the viscous layer limits the rate of displacement within the fault. A viscosity threshold could thus be defined above which the nucleation of new faults is made necessary to accommodate the boundary shortening rate. The model setup is first introduced followed by 2D numerical results.

2. Model Setup

[5] The model setup consists of a brittle layer rimed by two ductile layers (Figure 1). A displacement U (at a constant velocity V) is imposed at the bottom of the model, while the top is pinned. The two vertical boundaries are free. Mechanical equilibrium is solved by numerical means, using the finite-element code SARPP [*Leroy and Gueydan*, 2003], which accounts for finite strain. The displacement vector is the only nodal unknown. In this configuration, both brittle and ductile layers undergo the same amount of shortening. Brittle-ductile coupling will prevail at the two vertical brittle-ductile interfaces.

[6] The two ductile layers behave as an incompressible Newtonian fluid of viscosity η, so that the equivalent shear stress is linearly related to the strain rate. The brittle layer behaves as a pressure-independent Von Mises associated elasto-visco-plastic material. Before yielding, the material is described by a classical linear elasticity law. Yielding occurs when the elastic shear stress exceeds the yield stress σ^y, which is a function of the equivalent plastic strain ε^p (Figure 1). Yielding is first marked by hardening, followed by softening. In natural deformed rocks, the hardening corresponds to the irreversible and cumulative formation and growth of cracks. The subsequent softening is essential to fully develop plastic shear bands. The use of Von Mises elasto-visco-plasticity forces the orientation

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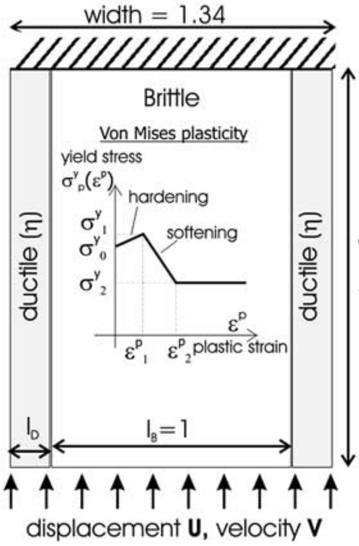

Figure 1. Model setup (length L = 2, brittle width l_B = 1, width of each ductile strip l_D = 0.1667; whole model discretized into 2400 square elements whose side length is 0.033) and boundary conditions. The brittle rheology is presented as inset in the brittle layer (Von Mises associated elasto-visco-plasticity: Young modulus E = 5.5 104, Poisson ratio $\nu = 0.25$, $\varepsilon_1^p = 0.02$, $\varepsilon_2^p = 0.12$, $\sigma_0^y = 90$; $\sigma_1^y = 100$, $\sigma_2^y = 60$).

of the faults to be at 45° with respect to the principal compression axis, since it is a pressure independent failure criterion. A plastic viscosity was introduced to avoid catastrophic fault propagation and was set to the same value in all simulations presented in this paper. Changing the value of the plastic viscosity did not change the fracture pattern, but did modify the timing of its development.

[7] This model is a first attempt to appreciate the mechanics of brittle-ductile coupling. However, the model setup is far from geological layering, since heat conduction and gravity are disregarded. The presence of the two ductile layers around the brittle layer is proposed here to avoid singularities effects at the corner of the system and to constrain first the level of fracturing in a Von Mises brittle layer as a function of the viscous strength. An important improvement will be to account for a temperature sensitive viscosity in order to model more accurately the brittle-ductile coupling in the lithosphere.

3. Results: Role of Ductile Viscosity on Brittle Fracturing

[8] In order to constrain the role of the ductile layer on the behaviour of the brittle layer, we have systematically varied the ductile viscosity η between 1 and 10000. The model setup and the Von Mises associated elasto-visco-plasticity law remain unchanged in the different models (cf. values in Figure 1).

[9] Figure 2 presents the plastic strain in the brittle layer as well as the equivalent shear stress (second invariant of the stress tensor) in both the brittle and ductile layers for three different viscosities (10, 100 and 1000) and for a displacement U of 0.15 (shortening of 7.5%). Faults can be identified by regions where the plastic strain is greater than 0.12 (end of softening; Figure 1). At 7.5% shortening, the fault pattern is developed. The larger the viscosity is, the denser the fault pattern is. As a consequence, the accumulated plastic strain on the faults is higher for low viscosity, because of the lower amount of faults. The densification of the fault pattern is particularly important in both central and extruded parts of the model.

[10] The fault zones are marked by low values of stresses (around 35–37) because of the softening that occurs within the fault. The fault edges are characterized by large stress values, which is characteristic of strain localization process. In the ductile layers, the shear stress is not homogeneous and its distribution is strongly dependent on the location of faults at the interfaces and on the value of the viscosity. The stress concentration at the corners of the layered structure (for η = 100 and 1000) is related to boundary conditions effects. These corner effects do not lead to faulting in the brittle layer. For low viscosities (η = 10), stress concentrations at fault tips are observed in the ductile layer, while for larger viscosity (η = 1000), the stress distribution is

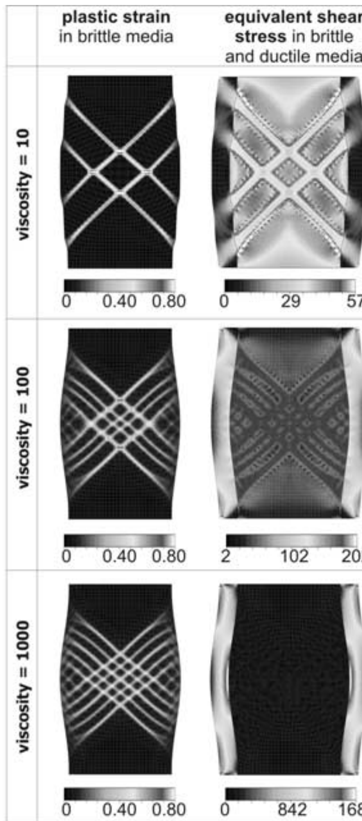

Figure 2. Distribution of the plastic strain ε^p in the brittle layer, and of the equivalent stress in the whole model for three different values of the ductile viscosity (η = 10, 100, 1000) for a displacement U of 0.15 (7.5% shortening). Note that the value of the equivalent shear stress in the fault zone (35–37) is slightly different from the microscopic shear stress imposed by the Von Mises yielding ($\sigma_2{}^y = 60$). These different values come from the definition of the equivalent shear stress, which is computed from the 3D state of stress. See color version of this figure in the HTML.

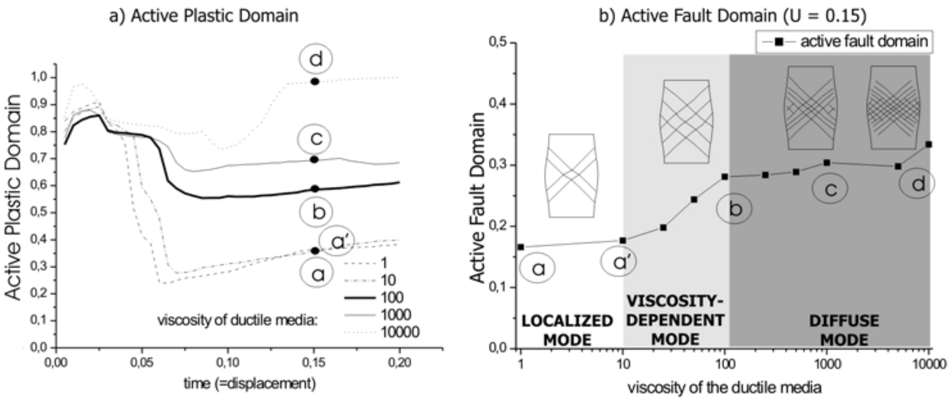

Figure 3. (a) Evolution of the Active Plastic Domain (APD) with time/displacement and for various viscosities. The Active Fault Domain (AFD) is shown in (b) as a function of the viscosity, for a shortening of 7.5% (points "a", "a'", "b", "c", and "d" of Figure 3a). The APD and the AFD are normalized by the area of the model. Results of Figure 2 correspond to points a′, b, and c.

more diffuse and maximum in the middle of the brittle-ductile interface.

4. Definition of the Macroscopic Brittle Deformation Modes

[11] From the above, two macroscopic brittle deformation modes can be defined: localized (η = 10) and distributed (η = 1000) modes. The role of the viscosity in the transition between these two modes as well as the timing for the onset and development of each mode of deformation are now explored in quantitative terms.

[12] For that purpose, the Active Plastic Domain (APD) and the Active Fault Domain (AFD) have been defined. The APD is defined by regions where the plastic strain and strain-rate are non zero ($\varepsilon_p \neq 0$, $\dot{\varepsilon} \neq 0$). The APD thus defines regions that always accumulated plastic strain (e.g., localized plastic zones). The AFD is a sub-region of the APD, where the plastic strain is larger than 0.12 (end of microscopic softening; Figure 1). The AFD thus defines the faults within the APD.

[13] The evolution with time of the APD is presented in Figure 3a for viscosities ranging between 1 and 10 000. The AFD is represented in Figure 3b, at 7.5% shortening (U = 0.15), as a function of the viscosity. For all viscosities, the APD shows a similar time evolution in three steps: (1) a small increase followed by (2) a decrease, which magnitude depends on the viscosity, and finally, (3) a stabilization, except for very high viscosities. These three stages could be related to the microscopic yielding history (Figure 1). The maximum value of the APD ($\sim$1) is reached for a displacement of around 0.025. This value is very close to ε_1^p = 0.02 that marks the end of microscopic hardening (Figure 1). For larger displacement, the decrease of the APD until a displacement of $\sim$0.07–0.1 is related with the microscopic softening that ends up for ε_2^p = 0.12 (Figure 1). The amount of the decrease of the APD strongly depends on the viscosity and could be related to the amount of faults created at the end of that decrease, as it is shown by the AFD (Figure 3b). For low viscosities (1 and 10), the decrease of the APD is very fast and the AFD is small and does not depend on the viscosity (0.17, points a and a′). Deformation tends thus to localize in a restricted number of faults (localized mode of fracturing). For larger viscosities, the decrease of the APD requires more shortening and the AFD is larger. For viscosities ranging between 10 and 100, a viscosity-dependent mode can be defined, in which the AFD increases with the viscosity. For larger viscosities (η > 100), the brittle deformation mode is distributed. The AFD is again independent of viscosity and its value is about twice that of the localized deformation mode.

5. Discussion

[14] These observations provide some hints of the mechanisms responsible for the brittle-ductile coupling that takes place at the brittle-ductile interface. For low viscosities, the mean stress in the ductile layer is almost entirely controlled by the displacement at fault tip, with a spatial pattern that resembles the classical elastic solution at crack tips (Figure 2, η = 10). The viscous stresses induced by the fault displacement are lower than stresses within the brittle layer, so that the functioning of fault is barely affected by these viscous boundary conditions. On the contrary, for large viscosities, the viscous stresses around fault tip can become much larger than the stresses within the brittle layer (Figure 2, η = 100). The ductile deformation related to fault motion limits the fault displacement rate, as a kind of a fault viscous friction. This viscous dissipation also yields an increase of the average brittle stress, but this effect is limited by the intrinsic yield strength of the brittle material. The increase of the number of faults is thus a direct consequence of this limitation of the displacement rate per fault due to this "viscous friction", since it may become necessary to create several faults to accommodate the boundary shortening rate.

[15] According to this reasoning, we can try to estimate the viscosity threshold, above which the nucleation of new faults is made necessary. The viscous stress within the ductile layer due to fault motion is about the fault displacement rate v_F multiplied by the ductile viscosity η, and divided by a characteristic length scale ξ that is likely to depend on the boundary conditions, on the width of the

ductile layer, and on the geometry of the fault tip. The maximum displacement rate is calculated by assuming that the viscous stress within the ductile layer due to fault motion cannot exceed the yield strength of the brittle layer σ_1^y; the viscosity threshold corresponds to the point where the maximum rate is just equal to the actual displacement rate due to boundary conditions. If the viscosity increases above this value, it is necessary to create a new fault in order to decrease the displacement rate per fault. The viscosity threshold η_c, computed for two pairs of 45° oriented faults (η = 10, Figure 2) so that $v_F = \frac{\sqrt{2}}{4}V$, reads:

$$\eta_C = \frac{2\sqrt{2}\sigma_1^y \xi}{V}$$

Assuming that ξ is about half the width of the ductile strip as shown in Figure 2 (0.05–0.1), we obtain a viscosity threshold of about 14–28, which fits very well with the first transition observed in Figure 3. Following *Huismans et al.* [2005], the balance of energy dissipation between brittle and ductile layers could lead to a better estimate of this viscosity threshold. For sake of briefness, the present simple analysis is found useful to estimate the order of magnitude of the viscosity threshold, the energy dissipation balance analysis being postponed to a future work.

[16] At very large viscosity (Figure 2, η = 1000), we observe that the brittle domain cannot be broken anymore. Considering the boundary conditions and the fact that two dead triangles exist close to the indenters, this AFD value of 33% indicates that the whole central part of the model is deforming plastically. The preceding mechanism is no more valid because of the impossibility to create new faults, and the system is likely to behave as a classical plastic material. Obviously we do not expect this possibility to occur in natural systems.

[17] This concept of "viscous friction" on faults is potentially relevant to lithosphere conditions since brittle and ductile stresses are comparable across the brittle-ductile interface. Obviously the system is much more complex than the previous calculations, with a non-linear depth-dependent viscosity and a vertical coupling. But we believe that such simple concept could bring a simple theoretical framework to revisit the consequence of brittle/ductile coupling on fault organization.

6. Conclusion

[18] When shortening a Von Mises elasto-visco-plastic layer rimed by two Newtonian ductile layers, the viscosity of the ductile layer defines a change in the level of fracturing within the brittle layer. The brittle-ductile coupling process is attributed to the viscous drag applied to each fault, which may lead to a limitation of the fault displacement rate. Three modes of brittle fracturing could be defined: a localized and a distributed mode (for low and high viscosity, respectively) that are independent on the viscosity. Between these two modes, the amount of faults increases with increasing viscous strength (viscosity-dependent fracturing). A simple analysis shows that the density of fault depends on the ratio between the applied shortening rate and the maximum displacement rate per fault, which is limited by the viscous layer. This theory well predicts the transition observed between the localized fracturing mode and the viscosity-dependant fracturing mode.

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